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Joyner

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(54) **TRANSMITTER PHOTONIC INTEGRATED CIRCUIT (TxPIC) CHIPS UTILIZING COMPACT WAVELENGTH SELECTIVE COMBINERS/DECOMBINERS**

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(51) **Int. Cl.**

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(52) **U.S. Cl.** **385/37; 385/14; 385/24; 385/47**

(58) **Field of Classification Search** 385/37
See application file for complete search history.

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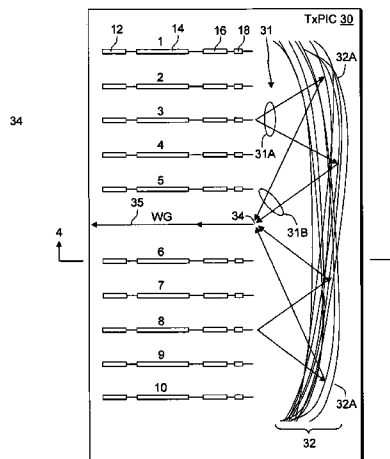
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(57) **ABSTRACT**

A monolithic transmitter photonic integrated circuit (TxPIC) chip and a monolithic receiver photonic integrated circuit (RxPIC) chip include a plurality of optical signal channels together with other active elements integrated on a semiconductor chip, which chips further include an optical combiner or decombinaer that is a wavelength selective comprising a supergrating or an Echelle grating which provides for a more compact chip compared to an integrated on-chip arrayed waveguide grating functioning as a wavelength selective combiner or decombinaer.

22 Claims, 10 Drawing Sheets



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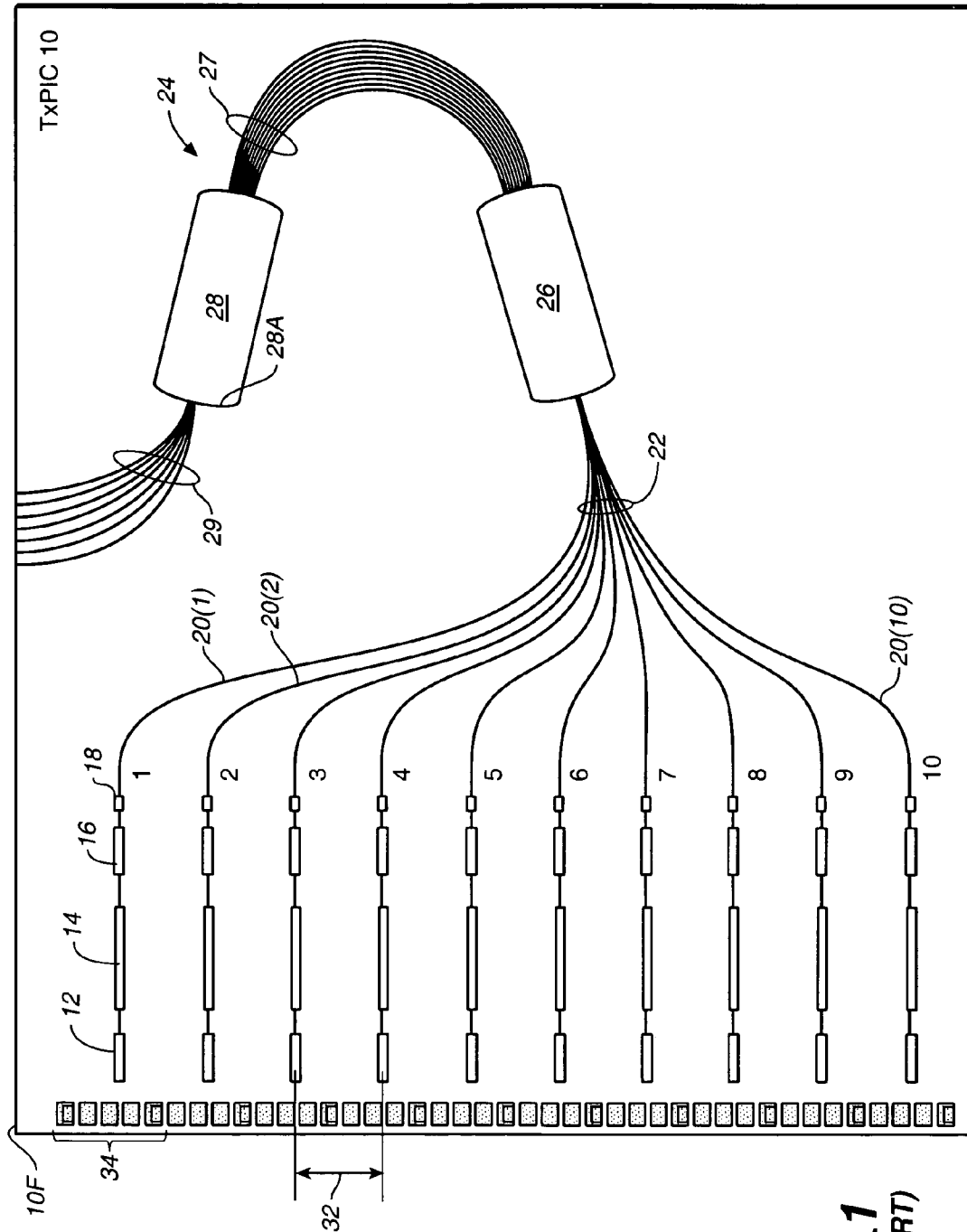


FIG. 1
(PRIOR ART)

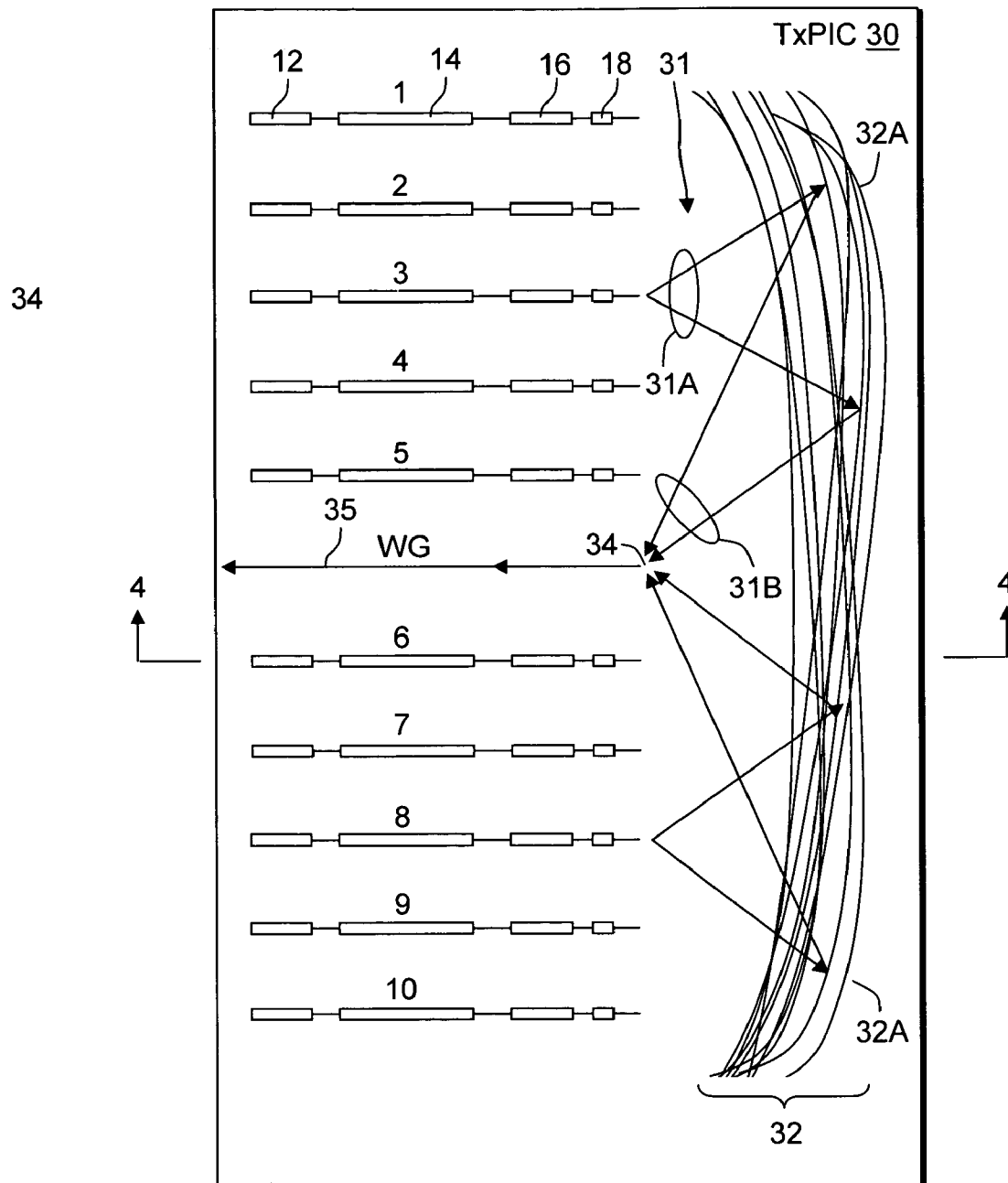


FIG..2

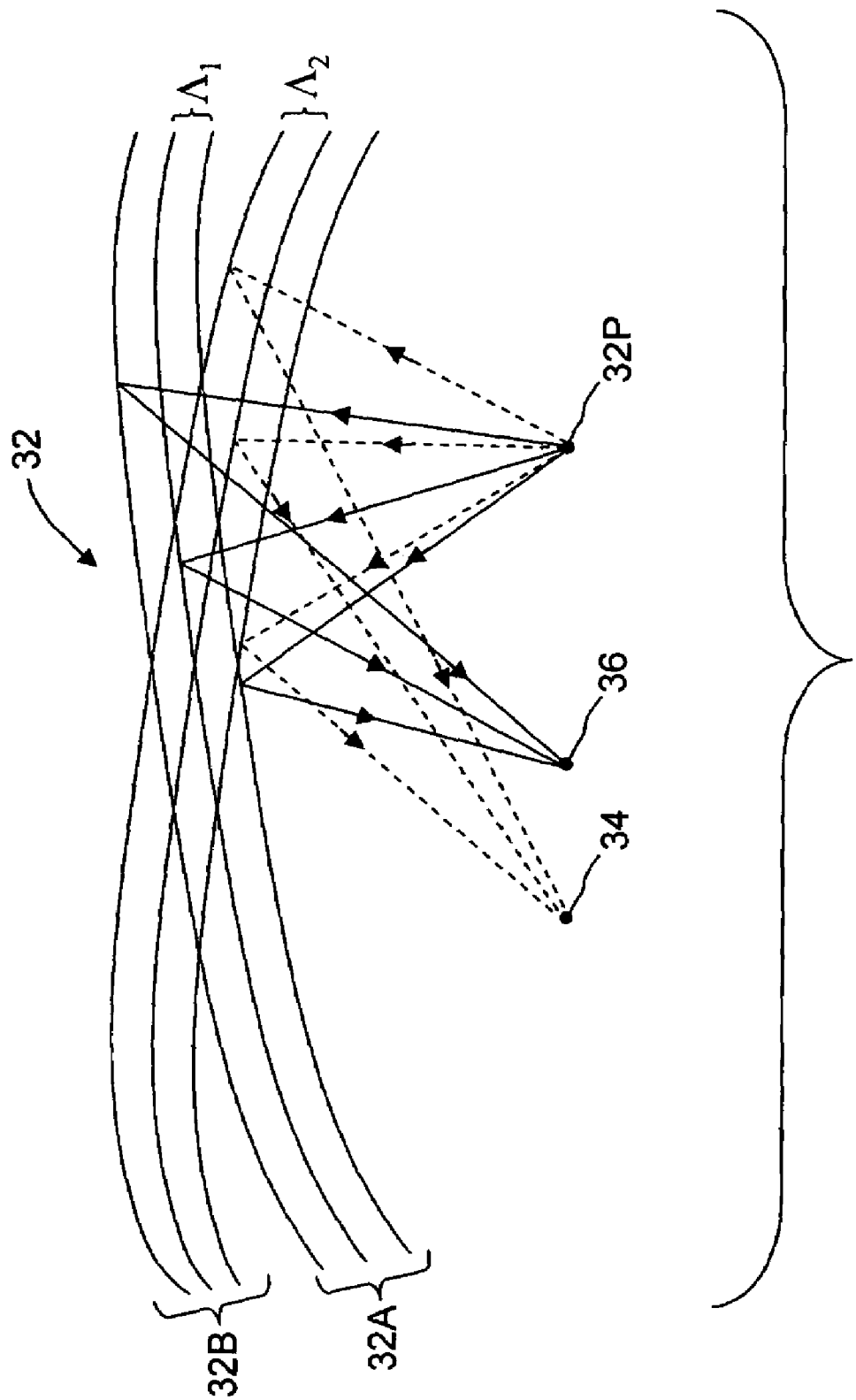


FIG. 3

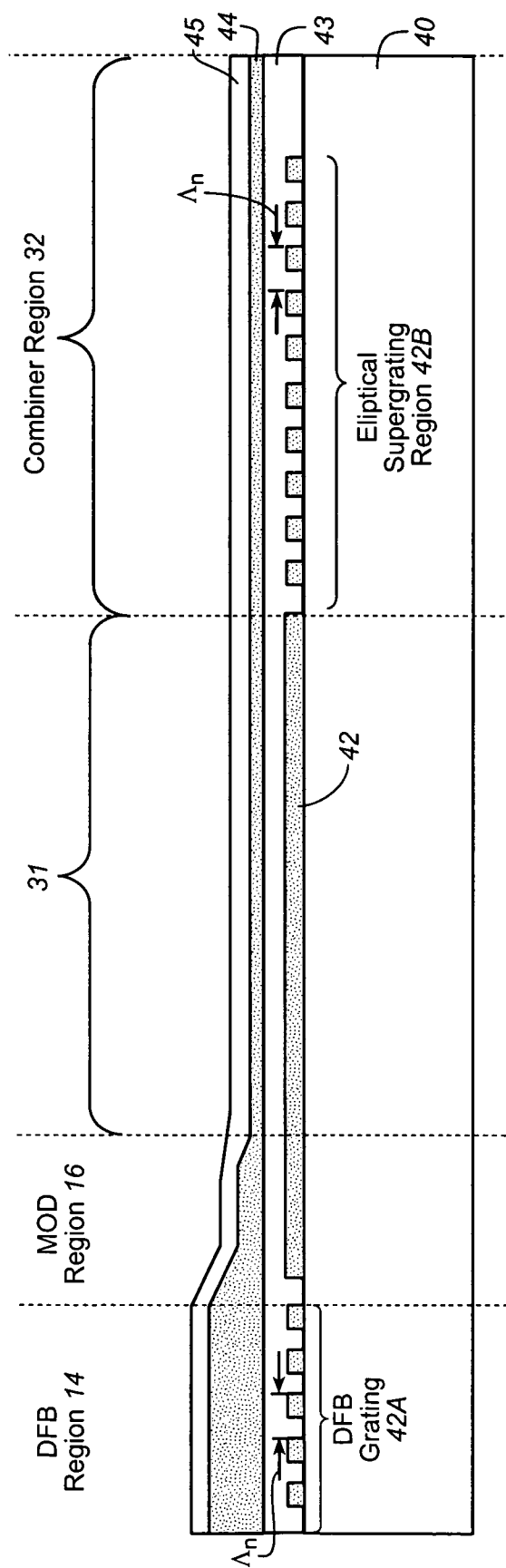


FIG. 4

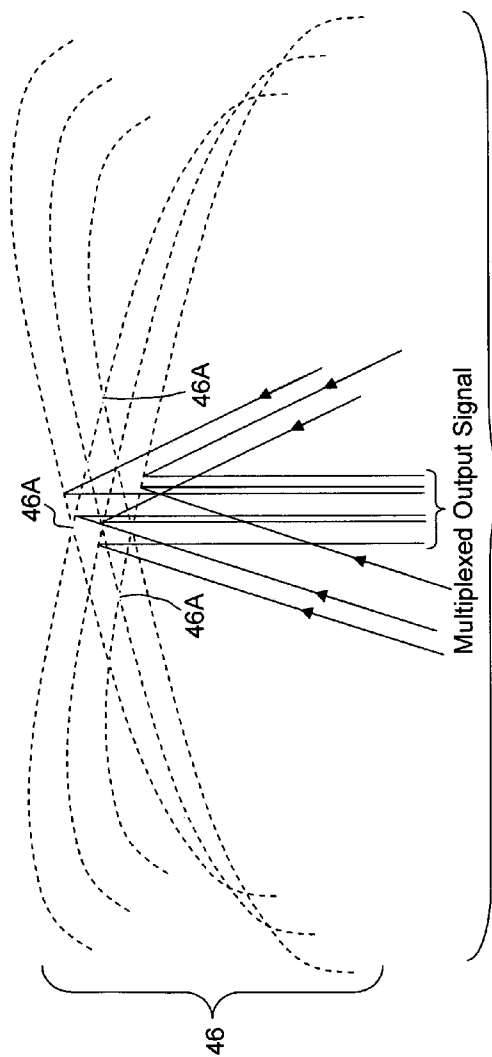


FIG. 5

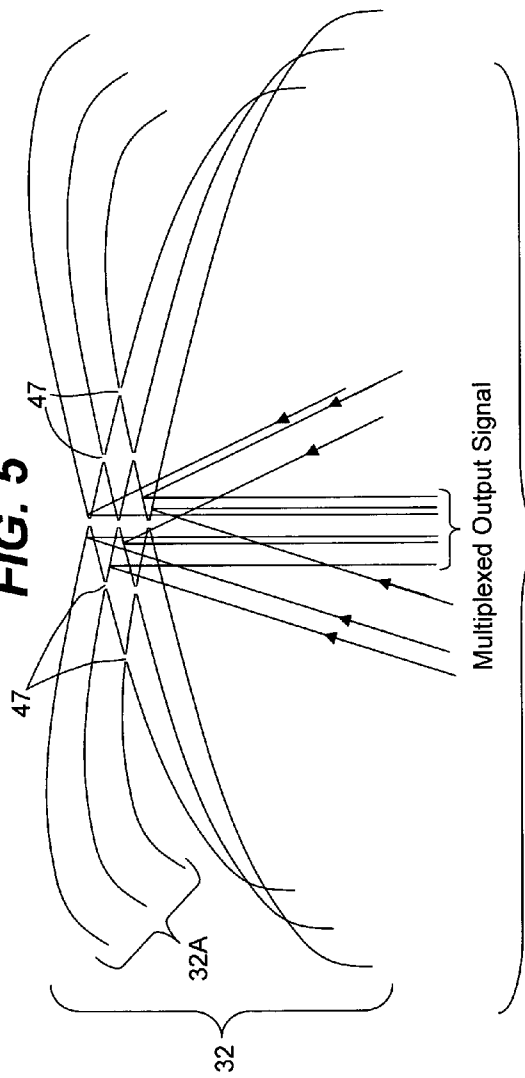
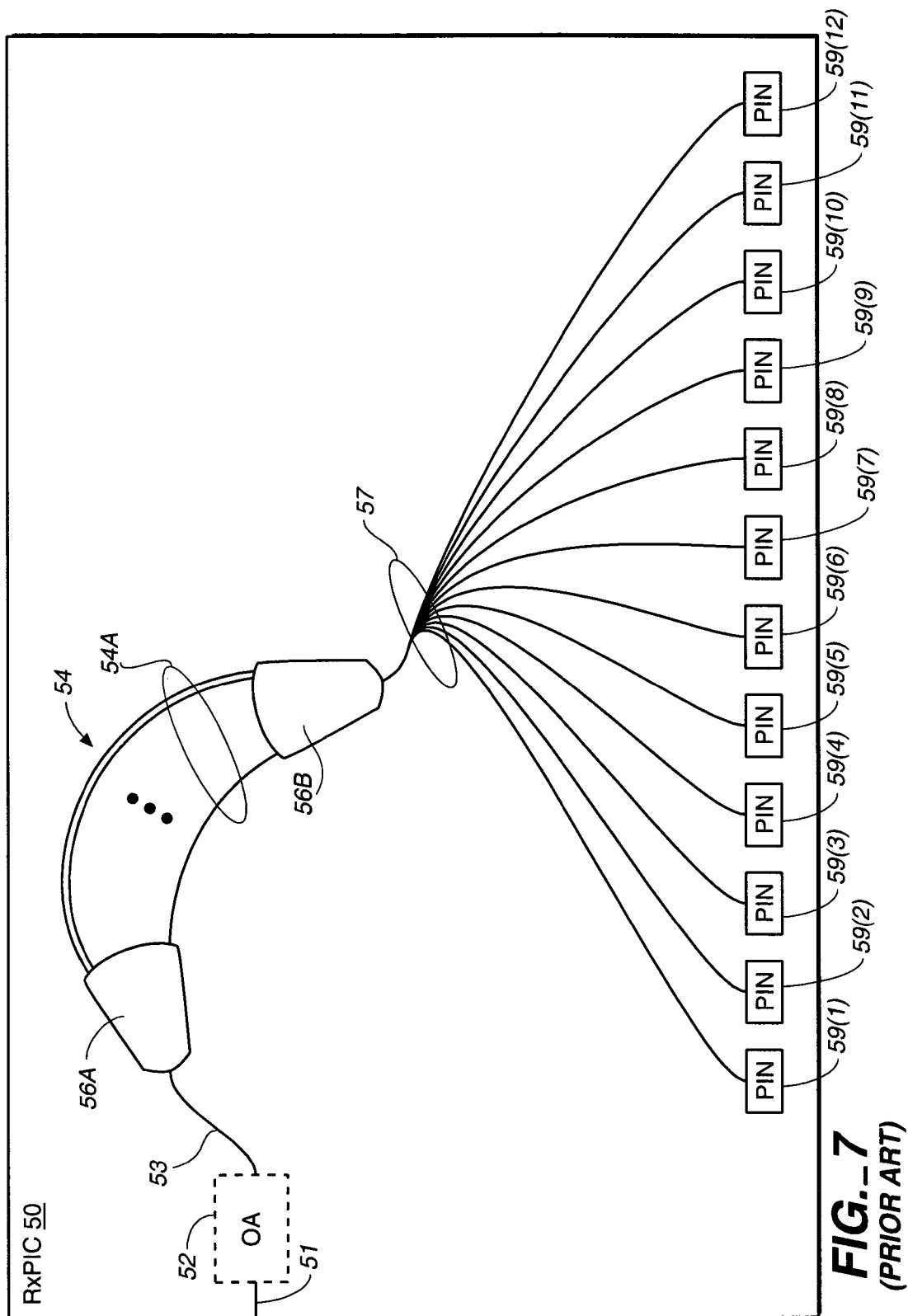


FIG. 6



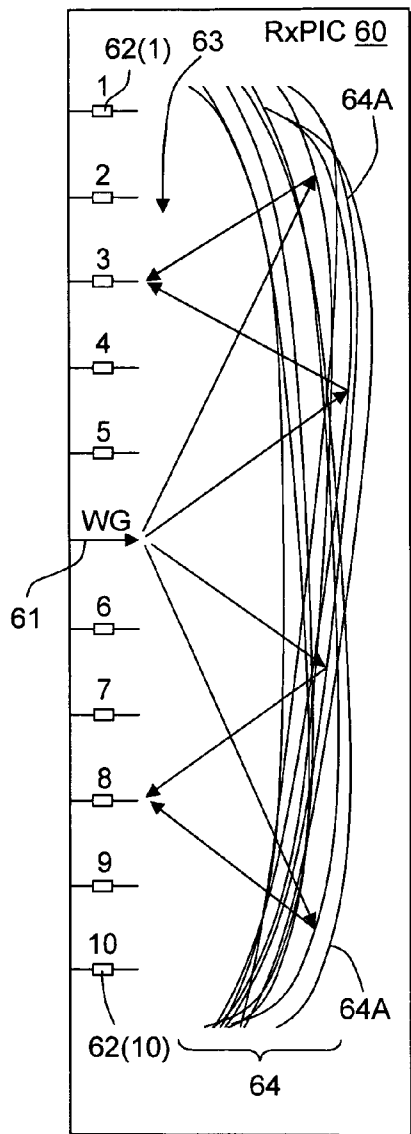


FIG..8

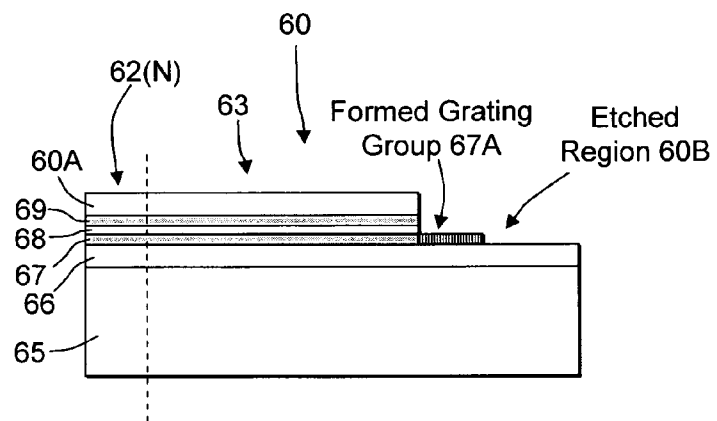


FIG..9

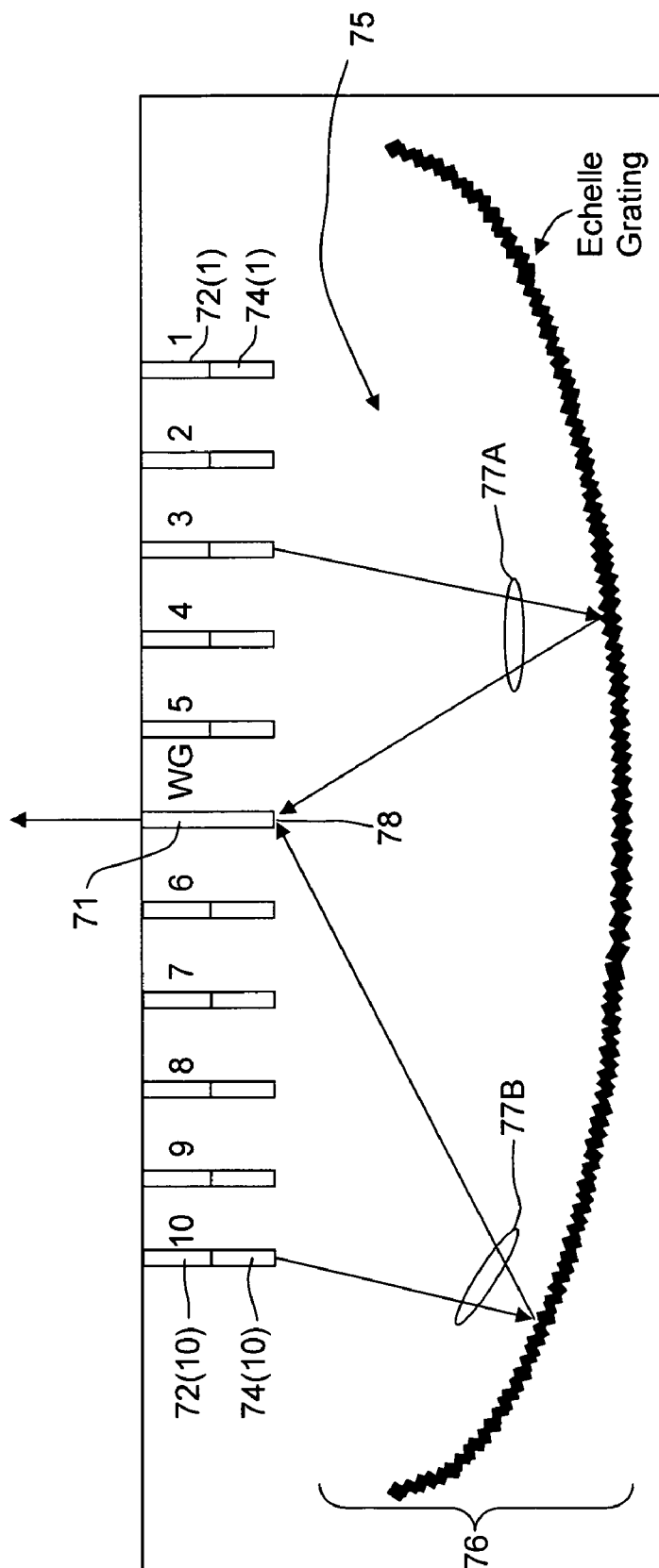


FIG. 10

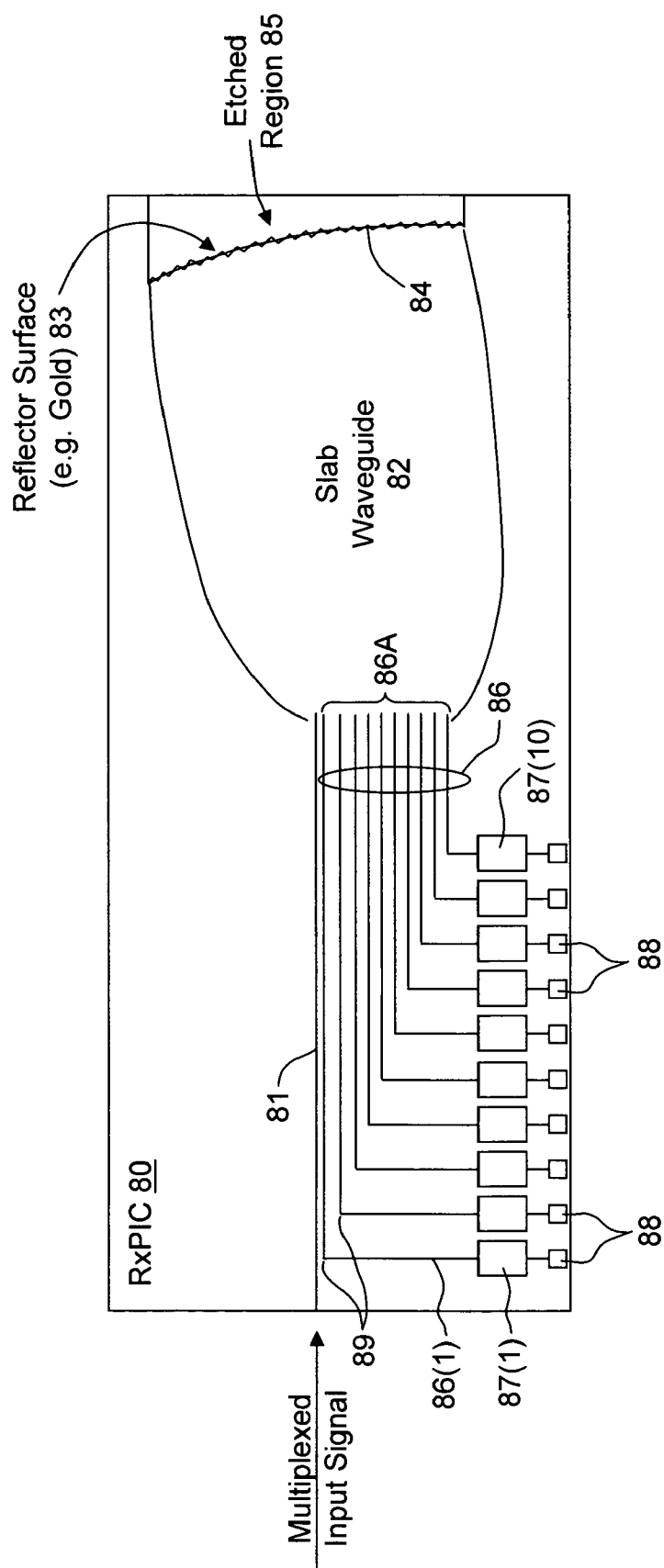


FIG. 11

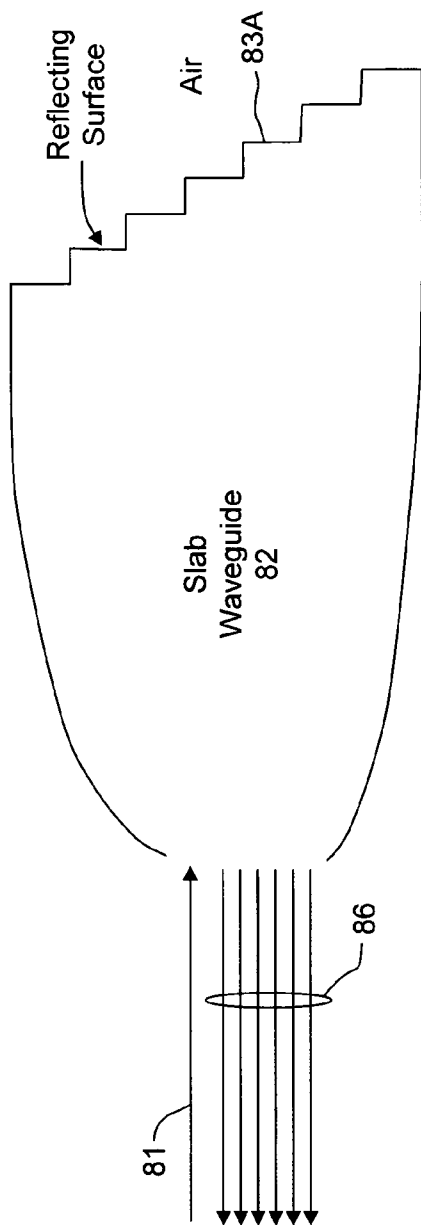


FIG. 12

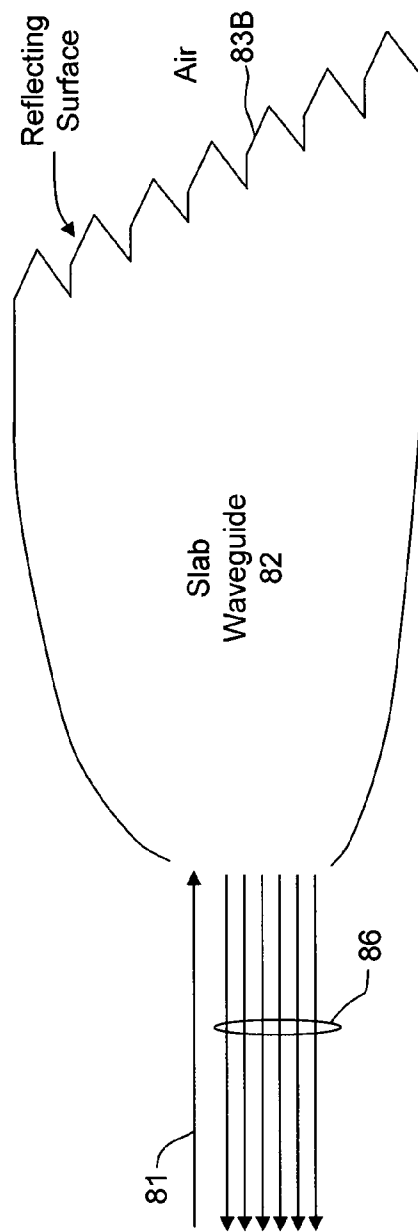


FIG. 13

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TRANSMITTER PHOTONIC INTEGRATED CIRCUIT (TxPIC) CHIPS UTILIZING COMPACT WAVELENGTH SELECTIVE COMBINERS/DECOMBINERS

REFERENCE TO RELATED APPLICATIONS

This application claims priority to provisional application, Ser. No. 60/470,570, filed May 14, 2003, which application is also incorporated herein by its reference, and is also a continuation-in-part of patent applications, Ser. No. 10/267,331, filed Oct. 8, 2002 and entitled, TRANSMITTER PHOTONIC INTEGRATED CIRCUITS (TxPIC) AND OPTICAL TRANSPORT NETWORKS EMPLOYING TxPICs, and published on May 22, 2003 as Pub. No. US 2003/0095737 A1; Ser. No. 10/267,304, filed Oct. 8, 2002 now U.S. Pat. No. 7,116,581 and entitled, AN OPTICAL SIGNAL RECEIVER PHOTONIC INTEGRATED CIRCUIT (RxPIC), AN ASSOCIATED OPTICAL SIGNAL TRANSMITTER PHOTONIC INTEGRATED CIRCUIT (TxPIC) AND AN OPTICAL TRANSPORT NETWORK UTILIZING THESE CIRCUITS, and published on Feb. 19, 2004 as Pub. No. US 2004/0033004 A1 now U.S. Pat. No. 7,116,851, issued on Oct. 3, 2006; Ser. No. 10/267,330, filed Oct. 8, 2002 now U.S. Pat. No. 7,079,715 and entitled, TRANSMITTER PHOTONIC INTEGRATED CIRCUIT (TxPIC) CHIP ARCHITECTURES AND DRIVE SYSTEMS AND WAVELENGTH STABILIZATION FOR TxPICs, published on May 22, 2003 as Pub. No. US 2003/0095736 A1 now U.S. Pat. No. 7,079,715 issued on Jul. 18, 2006; and Ser. No. 10/267,346, filed Oct. 8, 2002 now U.S. Pat. No. 7,058,246 and entitled, TRANSMITTER PHOTONIC INTEGRATED CIRCUIT (TxPIC) CHIP WITH ENHANCED POWER AND YIELD WITHOUT ON-CHIP AMPLIFICATION, published on May 1, 2003 as Pub. No. US 2003/0081878 A1 now U.S. Pat. No. 7,058,246, issued on Jun. 6, 2006, which applications are owned by the common assignee herein and are incorporated herein by their reference.

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates generally to photonic integrated circuits (PICs) and more particularly to multiplexers (MUXes) and demultiplexers (DEMUXes) employed in photonic integrated circuits (PICs). The devices disclosed here are more particularly for use in optical transmitter photonic integrated circuits (TxPICs) and optical receiver photonic integrated circuits (RxPICs) having an integrated on-chip optical combiner of the wavelength selective type, in particular, an elliptical supergrating MUX or DEMUX or a Echelle grating MUX or DEMUX, in lieu of an arrayed waveguide grating (AWG) MUX or DEMUX.

2. Description of the Related Art

The employment of monolithic photonic integrated circuits (PICs), also sometimes referred to as planar lightwave circuits (PLCs), are on the rise in deployment in optical telecommunication systems. These devices provide the integration of both active and passive optical components on a single substrate and are integrated with other optical components to form a multi-functional optical device for use in such systems. The gravitation to PICs is strong because it leads to utility of providing an entire system function, let alone a component function, in a single chip in a single package. Compared to the deployment of discrete optical components, such monolithic PIC chips can significantly

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reduce the size of optical components necessary in the optical system, albeit in a transmitter photonic integrated circuit (TxPIC) or a receiver photonic integrated circuit (RxPIC), for example, as well as significantly reduce the overall costs in a system. Examples of recent advanced TxPICs and RxPICs are disclosed in U.S. patent applications, Ser. Nos. 10/267,331; 10/267,304; 10/267,330; and 10/267,346, *supra*.

The size of a TxPIC InP-based chip having ten signal channels that comprise an array of ten laser sources, such as, for example, DFB lasers, and an array of corresponding electro-optic modulators, such as, for example, electro-absorption modulators (EAMs), and a wavelength selective combiner in the form of an arrayed waveguide grating (AWG) is about 4 mm by 4.5 mm. It would be desirable to reduce the size of such chips while simplifying the combiner structure and reducing its on-chip insertion losses.

One such candidate for an on-chip combiner is the elliptical supergrating MUX and DEMUX. An example of this type of device is disclosed in the article of Yankov entitled, "Multiwavelength Bragg Gratings and Their Application to Optical MUX/DEMUX Devices, *IEEE Photonics Technology Letters*, Vol. 15(3), pp. 410-412, March 2003 as well as in U.S. patent application publication No. 2003/0210862, published Nov. 13, 2003. Also, in particular the elliptical supergrating DEMUX is illustrated in U.S. patent application publication No. 2004/0036933, published Feb. 26, 2004 which discloses a so-called planar holographic multiplexer/demultiplexer comprising a series of curved or elliptical gratings that reflect different wavelengths and combines them at a predetermine output or input position. These gratings are referred to as holograms in the context that sets of such gratings being independently wavelength selective for a particular peak wavelength among other wavelengths in a multiplexed output and provide refractive index modulation and reflection of a selected peak wavelength. This publication also cites the previous work of Henry et al. entitled, "Four-Channel Wavelength Division Multiplexers and Bandpass Filters Based on Elliptical Bragg Reflectors", *Journal of Lightwave Technology*, Vol. 8(5), pp. 748-755, March, 2003 and in U.S. Pat. No. 4,923,271 which discloses a series of Bragg reflectors for reflecting multiple wavelengths from or to a central point of the combiner or decombiner. It is pointed out in publication No. 2004/0036933 that the Henry device has the disadvantage of not being scalable to high channel count because, since the gratings are spatially separated and will increase significantly with the number of added channels so that the device size becomes unyielding as well as its functionality significantly deteriorates. Publication '933 also mentions that in such two-dimensional devices, there may be the problem of intersection in the grating reflection field of the intersection of gratings of the supergrating to cross one another at intersections since the groups of subgratings are designed for different wavelengths. Moreover, if dashed lines are employed for the gratings, the spacing between dashes may be varied so that the reflection coefficient is enhanced and potential destructive interference (crosstalk) between intersecting gratings of different sets can be minimized. In other words, this destructive interference can be reduced to some extent by diminishing the overlap of the holograms or sets and this can be carried out by using dashed or dotted line gratings in the different sets. However, it is unclear how that might be successfully accomplished.

Another candidate is the Echelle grating for which much work has been published including, as examples, U.S. Pat. Nos. 5,206,920; 6,339,662; 6,141,152; and U.S. published

patent application, Publication No. 2002/0081061, as well as the article of Janz et al. entitled, "Planar Waveguide Echelle Gratings in Silica-On-Silicon", *IEEE Photonics Technology Letters*, Vol. 16(2), pp. 503-505, February, 2004.

While some of these publications indicate that these candidates can be used in photonic integrated circuits (PICs), such as in Publication No. '933 at page 6, paragraph [0083], there is no indication or teaching as to how this might be affected or accomplished.

OBJECTS OF THE INVENTION

It is an object of this invention to provide an integrated on-chip MUX or DEMUX that is more compact in size and easier to implement, compared to an arrayed waveguide grating (AWG) type of MUX or DEMUX, especially as integrated in a TxPIC or a RxPIC.

Other objects will become apparent throughout the remaining description of the invention.

SUMMARY OF THE INVENTION

According to this invention, a monolithic transmitter photonic integrated circuit (TxPIC) chip and a monolithic receiver photonic integrated circuit (RxPIC) chip include a plurality of optical signal channels together with other active elements integrated on a semiconductor chip or chips, which chips further include an optical combiner or decombinaer that is a wavelength selective comprising a supergrating or an Echelle grating which provides for a more compact chip compared to an integrated on-chip arrayed waveguide grating functioning as a wavelength selective combiner or decombinaer.

According to one embodiment of this invention, a monolithic transmitter photonic integrated circuit (TxPIC) chip comprises a plurality of N signal channels with each channel including a semiconductor laser optically coupled to an electro-optic modulator, each of the lasers having a different operational wavelength and each of the modulators receiving an electrical signal for modulating the CW light received from a corresponding laser. An integrated wavelength selective combiner on the TxPIC chip comprises an elliptical supergrating having an integrated common output to an output waveguide on the chip. In another embodiment, the integrated wavelength selective combiner may be an Echelle grating.

According to a further embodiment of this invention, a monolithic receiver photonic integrated circuit (RxPIC) chip comprises an integrated wavelength selective decombinaer for receiving a multiplexed multi-wavelength signal of N signal channels on an input waveguide to the combiner where the combiner is an elliptical supergrating. There is also a plurality of integrated N photodetectors on the RxPIC chip, each optically coupled to receive a respective demultiplexed channel signal from the supergrating for producing an electrical signal of a respective optical channel signal. In another embodiment, the integrated decombinaer may be an Echelle grating.

A still further embodiment of this invention is the method of forming a transmitter photonic integrated circuit (TxPIC) which has a grating layer where both the gratings for the laser sources as well as for the optical combiner may be formed, the latter being a supergrating or an Echelle grating.

BRIEF DESCRIPTION OF THE DRAWINGS

In the drawings wherein like reference symbols refer to like parts:

FIG. 1 is a plan view of a recently developed TxPIC chip that is disclosed in at least one of the previously incorporated

patent applications and utilizes an array waveguide grating (AWG) as an integrated multiplexer.

FIG. 2 is a plan view of a TxPIC chip utilizing an integrated elliptical supergrating as an on-chip multiplexer comprising this invention.

FIG. 3 is a diagrammatic view for the explaining of two different wavelength light beams interacting with two different subgrating sets of an elliptical supergrating.

FIG. 4 is a side longitudinal elevation of one of the signal channels of the TxPIC chip taken along the line 4-4 of FIG. 2 illustrating the grating layer in the TxPIC chip for forming all gratings.

FIG. 5 is a first alternative embodiment of the supergrating embodiment shown in FIG. 3.

FIG. 6 is a second alternative embodiment of the supergrating embodiment shown in FIG. 3.

FIG. 7 is a plan view of a recently developed RxPIC chip that is disclosed in at least one of the previously incorporated applications and utilizes an array waveguide grating (AWG) as an integrated demultiplexer.

FIG. 8 is a plan view of a RxPIC chip utilizing an integrated elliptical supergrating as an on-chip demultiplexer comprising this invention.

FIG. 9 is a side elevation of the RxPIC chip of FIG. 8.

FIG. 10 is a plan view of a TxPIC chip utilizing an integrated Echelle grating as an on-chip demultiplexer comprising this invention.

FIG. 11 is a plan view of a RxPIC chip utilizing an integrated Echelle grating as an on-chip demultiplexer comprising this invention.

FIG. 12 is a detailed view of a first type of grating that may be employed in the embodiments of FIGS. 10 and 11.

FIG. 13 is a detailed view of a second type of grating that may be employed in the embodiments of FIGS. 10 and 11.

DETAILED DESCRIPTION OF THE INVENTION

Reference is now made to the monolithic transmitter photonic integrated circuit (TxPIC) chip illustrated in FIG. 1. TxPIC chip 10 may be an InP-based chip, the structural details of which are disclosed in U.S. patent applications, Ser. Nos. 10/267,331 and 10/267,346, supra. As shown in FIG. 1, monolithic TxPIC chip 10 comprises groups of integrated and optically coupled active and passive components including an integrated array of laser sources 14, such as DFB semiconductor lasers or DBR semiconductor lasers. Each laser source 14 operates at a different wavelength, λ_1 - λ_N , from one another where the group of wavelengths provides a wavelength grid approximating a standardized wavelength grid, such as the ITU wavelength grid. The laser source wavelength grid is provided to have, as best as possible, a uniform or periodic channel wavelength pitch as well as a uniform channel width and with signal channel spacing set to, for example, 25 GHz, 50 GHz, 100 GHz or 200 GHz.

At the rear extent of laser sources 14, integrated rear photodetectors 12 may be provided, which are optional. Photodetectors 12 may be, for example, PIN photodiodes or avalanche photodiodes (APDs). Laser sources 14 may be directly modulated or may be operated CW and are provided with an associated external electro-optic modulator 16 as shown in the configuration of FIG. 1. Thus, the CW outputs of laser sources 12 are optically coupled to respective electro-optic modulators 16. Such light intensity modulators 16 may be electro-absorption modulators (EAMs) or Mach-Zehnder modulators (MZMs) as detailed in patent applica-

tion, Ser. No. 10/267,331, supra, but EAMs are preferred for operation here in conjunction with DFB laser sources. Modulators **16** each apply an electrical modulated signal to the CW light received from laser sources **14** producing a plurality of optical modulated signals of different wavelengths for transmission on an optical link in an optical transmission network. The modulated outputs from each modulator **16** may be optically coupled to a respective front photodetector **18**. The on-chip deployment of photodetectors **18** is optional. Alternatively, photodetectors **18** may also be fabricated off-axis of the laser source output by means of an on-chip optical tap to provide a small portion of the modulated output directed from the main optical channel path to the offset photodetector. Front photodetectors **18** may also be PIN photodiodes or avalanche photodiodes (APDs). Photodetectors **12** and **18** may also be employed together to monitor the output power or operational wavelength from the respective laser sources **14**. Alternatively or in addition, photodetectors **18** may also function as variable optical attenuators (VOAs) under negative bias in order to selectively adjust modulated source output power to equalize the optical output power across all of the laser sources **14** thereby providing on-chip pre-emphasis. Further, alternatively or in addition, photodetectors **18** may be employed as on-chip semiconductor optical amplifiers (SOAs) under positive bias. Photodetectors **18** functioning as VOAs or SOAs provide for pre-emphasis across the modulated source array. Also, as well understood in previously incorporated patent applications herein, photodetectors **12** and **18**, laser sources **14** and modulators **16** are electrically isolated from one another. Also, as a further embodiment, a different frequency tone may be applied to each photodetector **18** to provide for laser source tagging or identification as described and taught in U.S. patent Application, Ser. No. 10/267,330, supra.

As indicated above, and as explained in more detail in patent application Ser. No. 10/267,331, supra, the modulated optical signal outputs of modulators **16**, via front photodetectors **18**, are respectively coupled to an on-chip wavelength selective combiner, shown here as an arrayed waveguide grating or AWG **24** via N optical input waveguides **22**, equal to the number of N laser source/modulator combinations which are also referred to as N signal channels. In FIG. 1, there is a plurality of N-equal-10 channels on TxPIC chip **10**. There may be less than N=10 channels formed on chip **10** or there may be more than N=10 channels formed on chip **10**.

Also, it should be noted that the output capability of each laser source (DFB or DBR) is a sensitive function of the detuned gain peak, or equivalently the PL wavelength of the active region, from the designed laser source grating wavelength. Detuning can be defined as the difference in wavelength between the room temperature PL of the active region formed in the TxPIC and the designed operating wavelength the laser source as dictated by the periodicity, Λ , of the laser source grating. Performance gains over temperature can be obtained by designing the laser source grating with respect to gain peak such that alignment between the two improves at higher temperature operation.

As already indicated above, each signal channel is typically assigned a minimum channel spacing or bandwidth to avoid crosstalk with other optical channels. For example, 50 GHz, 100 GHz or 200 GHz are common channel spacings between signal channels. The physical channel spacing or center-to-center spacing **32** of the signal channels may be 100 μm , 200 μm , or 250 μm to minimize electrical or thermal cross-talk at higher data rates, for example, of 10 Gbit per

second or greater, and facilitate routing of interconnections between bondpads **34** of multiple PIC optical components or elements formed on the chip. Although not shown for the sake of simplicity, bonding pads may be provided in the interior of PIC chip **10** to accommodate wire bonding to particular on-chip electro-optic components in addition to chip-edge bonding pad groups **34**.

Referring again to optical combiner comprising an AWG **24**, the respective modulated outputs from signal channels are coupled into optical waveguides **20(1)** to **20(10)** to the input of AWG **24** as shown in FIG. 8. AWG **24** comprises an input free space region **26** coupled to a plurality of diffraction grating waveguides or arms **27** which are coupled to an output free space region **28**. The multiplexed optical signal output from AWG **24** is provided to a plurality of output waveguides **29** which comprise output verniers along the zero order Brillouin zone at output face **28A** of free space region **28**. Output waveguides **29** extend to chip output facet IOF of TxPIC chip **10** where a selected vernier output **29** may be optically coupled to an output fiber (not shown). The deployment of multiple vernier outputs **29** provides a means by which the best or optimum output from AWG **24**, or for any other optical signal combiner for that matter, may be selected by determining which vernier has the best match of the wavelength grid passband of AWG **24** for the established wavelength grid of channel signals provided from the array pairs of laser sources/modulators. Seven vernier outputs **29** are shown in FIG. 1. It should be realized that any number of such vernier outputs may be utilized. Also, the number of such vernier outputs may be an odd or even number.

In operation, AWG **24** receives N optical channel signals, λ_1 – λ_N , from coupled input waveguides **22** which propagate through input free space region **26** where the wavelengths are distributed into the diffraction grating arms or waveguides **27**. The diffraction grating arms **27** are plurality of grating arms of different lengths, by ΔL , from adjacent waveguides or arms, so that a predetermined phase difference is established in arms **27** according to the wavelengths λ_1 – λ_N . Due to the predetermined phase difference among the wavelengths in grating arms **27**, the focusing position of each of the signals in grating arms **27** in output free space region **28** are substantially the same so that the respective signal wavelengths, λ_1 – λ_N , are focused predominately at the center portion or the zero order Brillouin zone of output face **28A**. Verniers **29** provide various passband representations of the multiplexed signal output from AWG **24**. Higher order Brillouin zones along output face **28A** receive repeated passband representations of the multiplexed signal output but at lower intensities. The focus of the grating arm outputs to the zero order Brillouin zone may not be uniform along face **28A** comprising this zero order due to inaccuracies inherent in fabrication techniques employed in the manufacture of TxPIC chip **10**. However, with multiple output verniers, an output vernier can be selected having the best or optimum combined signal output in terms of power and strength.

Chip **10**, as well as chips disclosed in other embodiments herein, is preferably fabricated using MOCVD with a InP-based regime and the active region of chip **10** may be comprised of InGaAsP (“PQ”) or AlInGaAs (“AQ”). The active region may be a single or multiple layer configuration and is preferably a multiple quantum well region. Also, laser sources **14** are positively detuned, e.g., in the case of DFB lasers, the grating pitch of the feedback grating of the respective DFB lasers are chosen such that the laser operates on the longer wavelength side of the gain peak or PL peak of the active region. This detuning provides for laser per-

formance to be substantially uniform over a wider temperature range, in particular, the laser gain is maintained or actually increases some with increasing operating or ambient temperature. Laser sources **12** may be fabricated to operate at a positive detuned wavelength, for example, in the range of about 25 nm to about 40 nm from the gain peak. In the case of using electro-absorption modulators (EAMs) as modulators **16**, the DFB laser **14** detuned transmission wavelength is close to the absorption edge of the modulator active waveguide core insuring optimal wavelength compatibility between laser sources **14** and corresponding EAMs **16** without significantly degrading the performance of the laser sources due to the application of positive detuning.

In addition, chip **10** may include strip heaters (not shown) formed adjacent to or in close proximity to each laser source **12**. These heaters are employed to fine tune the operating wavelengths and, therefore, the resultant operational wavelength of laser sources **14** in the laser source array.

Reference is now made to FIG. 2 which discloses a TxPIC chip **30** utilizing a supergrating **32** as the optical signal combiner comprising this invention. Chip **30** is notably much smaller in size compared to TxPIC **20**, e.g., as much as about 2.5 times smaller in chip area. Chip **30** includes, in the example illustrated here, N=10 signal channels each comprising a modulated source **12** and **14** with front photodetector **18** and rear photodetector **12**. As indicated previously, N may be any other value that is physically and economically feasible for placement on a monolithic chip. However, instead of utilizing an AWG **24** as an on-chip multiplexer, an elliptical supergrating **32** is utilized and comprises a plurality of subsets of elliptical gratings where each subset has a grating period, Λ_n , for reflecting the linewidth of a given peak wavelength of each respective laser source **12** of optical channels **1** to **10** according to the equation,

$$\lambda_n = 2n\Lambda_n.$$

Supergrating multiplexer **32** is made by cascading a series of elliptically-shaped mirrors which are referred to in this disclosure as sets of subgratings **32A** where each N set for N signal channels has a different grating period, Λ_n . Each set of gratings is reflective for the wavelengths within the stop band of the subgratings which may be, for example, about 1.2 nm. The stop band of a set of subgratings may be made to overlap employing a phase shift in the grating, as is known in the art, so that the stop band may be broadened to about 1.6 nm.

In FIG. 2, the representation of these subsets of gratings is a single elliptical line **32A**, and, therefore, there are N=10 such subgrating sets or groups **32A**. Each of these subgratings sets **32A** are comprised of etched grooves in a grating layer **42A** (FIG. 4) of the epitaxial grown structure comprising TxPIC **30**, which will be explained in more detail later. There is a free space region **31** wherein the modulated output from the respective ten channels enters into and the respective modulated outputs of the N channels are permitted to expand (diverge as in a point source), such as indicated at **31A**. Then, these modulated beams respectively encounter a particular elliptical subgrating set **32A** having grating period, Λ_n , that substantially matches the peak wavelength, λ_n , of a respective beam and, as a result, the beam is totally, internally reflected by the elliptical subgrating set and refocused to a common output **34** which is the input end of the chip central output waveguide **35**, such as indicated by arrows **31A** and **31B**. The advantages of this design are that beside being more compact than the deployment of an AWG **24**, the path lengths are more uniformly the

same from end of the channel array to the other with the output waveguide **35** preferably in the center between the split groups of signal channels, i.e., between channel **5** and channel **6**. Characterized this with the AWG **24** where one of the paths or grating arms **27** that is the longest suffers the most insertion loss than the other AWG arms which are all shorter than this longest arm. As a result, the power among the channel signals at the output of the AWG will not be uniform. However, in the case of supergrating **32** and the architecture of FIG. 2, the path lengths of each of the N channels to supergrating and back are substantially smaller than the path lengths in a corresponding AWG. In an AWG **24** (FIG. 1), these path lengths can be as long as 7 mm whereas in supergrating **32**, the path lengths are in the neighborhood of 1.8 mm. Having said the foregoing, it should be noted that the output **35**, instead of being in the center of chip **30**, may be positioned at any location of any one of the N channels in spite greater change in the respective path lengths, in which case they still would not be as long as the curved path lengths in AWG **24**. However, the preferred embodiment is to place the TxPIC output waveguide **35** at the center of the chip because the power loss is minimized in this configuration because there are less propagation path lengths for the light in each case to travel to a common output. However, this embodiment is not infinitely scalable so that there is a limit to how many signal channels can be formed on the chip since eventually the path lengths of the outer most channels will become too long and provide a significant penalty compared to the inner most signal channels in proximity to on-chip waveguide output **35**.

In FIG. 3, a simple example of an elliptical supergrating **32** is shown consisting of two subgrating sets **32A** and **32B** are shown where each subset comprises three subgratings having different grating periods, Λ_1 and Λ_2 . In practice, however, such subgrating sets may have 100 to several 1,000 of such subgratings in each set. The subgrating groups **32A** and **32B** are angularly disposed relative to elliptical focal point **32P** to provide, upon reflection, respective focal points **36** and **34** adjacent to elliptical focal point **32P**. As seen in this figure, light diverging from point **32P** having a wavelength λ_1 will be reflected from the subgrating set **32A** having a period, Λ_1 , and is refocused to point **36**. On the other hand, light diverging from point **32P** having a wavelength λ_2 will be reflected from the subgrating set **32B** having a period, Λ_2 , and is refocused to point **34**. Of course the opposite is true in the case where point (laser) sources would be at points **34** and **36** and are refocused to common output port or waveguide at point **32P** as would be the case for TxPIC **30** in FIG. 2.

FIG. 4 is a cross-sectional side elevation of TxPIC chip **30** in FIG. 2 at line 4—4 except that for purposes of simplicity, photodetectors **12** and **18** are not included in either view. Also, a completed epitaxial structural layered device is not shown in that only the layers up to the active region of the PIC are illustrated. More details of these devices can be seen in previously incorporated U.S. patent applications. As shown in FIG. 6, chip **30** comprises a substrate **40**, which may be InP, followed by grating layer **42** of AQ or PQ. There may be an intervening buffer and cladding layer of InP between substrate **40** and grating layer **42**. This completes an initial MOCVD epitaxial growth step whereupon DFB gratings **42A** for laser sources **14** are formed using conventional techniques such as photolithography with dry or wet etching, e-beam writing, or holographic beam writing to form the gratings with their proper grating pitch or period, Λ_n , for each of the respective laser sources **14**. Each different

period, Λ_n , provides for a different operational wavelengths that correspond or approximate the wavelengths along a standardized waveguide such as the ITU grid in the C band or L band, for example. Concurrently with the forming of these laser source gratings, the supergrating 42B is correspondingly produced in this same step in combiner region 32 where the sets of subgratings 32A are formed by the same processes with proper grating pitch or period, Λ_n , where $\lambda_n = 2n\Lambda_n$ to form an elliptical supergrating 32. This grating process is followed by the formation of layer 43 such as, for example, InP, which provides the differential modulated refractive index, n , for these gratings to perform substantially total internal reflection at the prescribed wavelengths λ_n . The epitaxial growth of layer 43 is followed by the growth of active region 44 which may be comprised of multiple quantum wells and barriers of AQ or PQ as known in the art. This is followed by the epitaxial growth of a confinement layer 45 of InP, for example, as well as other layers, such as a stop etch layer, cladding layer and cap layer. The advantage of deploying supergrating 32 at 42B as an optical combiner is that it may be fabricated concurrently with the laser source gratings 42A which is not true for an AWG type optical combiner. With an AWG, the active region 44 over combiner region 32 may preferably be removed and regrown to have an appropriate refractive index to be more transparent to the generated channel signal wavelengths. This regrowth step is not necessary when deploying a supergrating as the optical combiner. Also, as previously mentioned, supergrating 32 does not require as much real estate on chip 30 to perform the same functions as an AWG 24 (FIG. 1).

In FIGS. 2 and 3, supergrating 32 is illustrated as series of continuous elliptical shaped arcs. However, as known in the art, these gratings may be dashed-line gratings as illustrated for the sets of subgratings 46 in FIG. 5. Also, intersections or crossing points 46A of the different sets of subgratings 46 may be provided such that one set is provided with opened spaces 46A at these intersections relative to another set of subgratings 46 so that there is no lined crisscross or sharp points at these subgrating intersections causing undesired destructive interference including crosstalk. As an example, these open intersections 46A at grating crossings may be, for example, about 5 μm . In this manner, less optical interference, such as crosstalk, is created between adjacent subgrating sets, caused by destructive light interference at these crosspoints, resulting in better combiner performance. The depth of the gratings may be, therefore, in this embodiment as well in the embodiment of FIG. 6 a little deeper compared to the depth of the laser source gratings, such as, for example, about 90 μm deep whereas the laser source gratings are approximately 50 μm deep.

Such reduced optical destructive interference can also be reduced in solid line subgratings 32A as illustrated in FIG. 6 where the intersections 47 are opened spaces with no grating. This can be performed employing e-beam writing of these gratings by discontinuing the subgratings at crisscross points 47. While this may enhance combiner optical losses, a substantial portion of the respective wavelength signals forming the multiplexed output signal beam will undergo internal reflection by the multiple subgratings relative to each such set of subgratings producing a multiplexed output signal beam. In this connection, a gain-clamped semiconductor optical amplifier (GC-SOA) or semiconductor optical amplifier (SOA) may be provided in the output

waveguide 35 of chip 30 or optionally an optical amplifier may be employed at the output of chip 30, such as, for example, an EDFA.

Reference is now made to FIG. 7 which shows the typical layout for a monolithic receiver photonic integrated circuit (RxPIC) chip 50. It should be noted that RxPIC chip 50 is just one embodiment of many that may be employed in a digital optical transmission network. See, for example, the different embodiments illustrated in U.S. patent application Ser. No. 10/267,304, *supra*. In this embodiment, provision is made for an on-chip integrated optical amplifier (OA) 52 on RxPIC chip 50, such as a semiconductor optical amplifier (SOA) or a gain-clamped semiconductor optical amplifier (GC-SOA). Optical amplifier (OA) 52 may be integrated on the chip to boost the gain of the multiplexed signal prior to demultiplexing. Such amplification can alternatively be done off-chip with an optical fiber amplifier, such as with an EDFA, prior to the input of signal into on-chip waveguide 51. RxPIC 50 may be an InP-based semiconductor chip that has an input at waveguide 51 to receive a multiplexed optical signal such as from an optically coupled fiber link. The multiplexed signal received in chip waveguide 51 is provided as an input to decombiner 54 which is an AWG demultiplexer 54. The multiplexed signal is provided to input slab or free space region 56A of AWG 54. AWG 54 comprises input slab 56A, an array of grating waveguides or arms 54A of different lengths and an output slab 56B as known in the art. Output slab 56B has a plurality of output waveguides 57 in the zero order Brillouin zone, one for each demultiplexed channel wavelength signal, which are respectively provided to PIN photodiodes 59(1) . . . 59(12). Although there are twelve channels shown here for chip 40, there may be less than or more than twelve such channel signal outputs from AWG 54 to corresponding photodetectors 59. The photocurrents developed in photodetectors 59 are taken off-chip to a TIA circuit, as known in the art, to produce modulated voltage signals that correspond to the demultiplexed and detected optical signals.

Reference is now made to FIGS. 8 and 9 which disclose an embodiment comprising this invention comprising RxPIC chip 60 having an input waveguide 61 for receiving a multiplexed optical signal from an optical link. Waveguide 61 is coupled to a free space region 63 for directing the incoming multiplexed optical signal to supergrating 64 comprised of a sets of subgratings 64A which function in the same manner as supergrating 32 in TxPIC 30 of FIG. 2 except that, here, the multiplexed signal in waveguide 61 is demultiplexed and the individual demultiplexed, modulated channel signals are reflected back to focal points comprising waveguides containing photodetectors 62(1) . . . 62(10) or can be focused directly to inputs of these photodetectors themselves. Photodetectors 62 may be, for example, PIN photodiodes or an avalanche photodiodes. The photocurrent signals produced by photodetectors 62 are then taken off-chip for electronic processing. Supergrating 64 is made in the same manner as previously explained for supergrating 32 and also can have the configurations as disclosed and explained in connection with FIGS. 5 and 6. FIG. 9 is an illustration of a side elevation of RxPIC 60 which may be comprised of a substrate 65, such as InP, followed by a cladding layer 66, such as, for example, of InP, followed by grating layer 67, such as, for example, comprising AQ or PQ, followed by space layer 68 of InP, followed by active core layer 69, such as, for example, comprising AQ or PQ, followed by light absorption layer 60A for photodetectors 62(N) which may be, for example, comprised of PQ which is larger than core layer 68 to function as a carrier mass

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transport layer. Layer 60A may then be followed by a cladding layer and a cap layer (not shown). Upon completion of the epitaxial growth, the region of supergrating 64 is etched back, as indicated at 60B, and supergrating 64 may be formed in the manner as previously explained wherein grooves or troughs forming the groups or sets of subgratings 64A are formed or written into grating layer 67 at region 67A. The advantage in deploying supergrating 64 in lieu of AWG 54 in an RxPIC is that the area of the chip can be made significant smaller with the deployment of a supergrating demultiplexer 64 compared to that required for an AWG demultiplexer 54. Thus, the package for RxPIC chip 60 can be made smaller or more IC chips, such as TIA IC chip or AGC IC chip can be placed within the same package as RxPIC chip 60 with package leadout pins for coupling to inputs of an TIA/AGC chip as well as pins for bias leads for operating photodetectors 62(1) . . . 62(10).

FIG. 10 illustrates another embodiment of this invention comprising TxPIC 70 comprising N=10 signal channels comprising laser sources 72(N) and associated modulators 74(N) and a center channel output waveguide 71. Chip 70 in FIG. 10 is notably much smaller in size compared to TxPIC 10 in FIG. 1, e.g., as much as about 1.5 times smaller in chip area. In the embodiment here, the optical combiner comprises an Echelle grating 76, as shown in FIG. 10, rather than an AWG 24 as shown in FIG. 1. The outputs of modulators 74(1) . . . 74(10) are separated from Echelle grating by free space region where the respective channel signals from the modulators are permitted to diverge in region 75, as illustrated by arrows 77A and 77B, and then all reflected by Echelle grating 76 and refocused to a common output point 78 at output waveguide 71 for exit from chip 70 as a multiplexed optical signal comprising 10 channel signals.

FIG. 11 illustrates RxPIC chip 80 which illustrate a decombiner comprising an Echelle grating 84 functioning in a manner as illustrated in U.S. Pat. No. 6,339,662, which patent is incorporated herein by its reference. Echelle grating 84 differs from that patent in that a photodetector array 87(N) is integrated on chip 80. Also, and importantly, Echelle grating 84 is etched into chip 80 via etched region 85 so that free space region 82 is a slab comprising a waveguide core formed in chip 80 such as AQ or PQ region in an InP-based chip. In this manner, a high performance reflecting surface 83 may easily be deposited on the external face of grating 84, such as gold or a dielectric stack, for example, a six-layer dielectric stack to provide a high quality mirror surface as known in the art. Also, exposed grating surface 83 must be very perpendicular relative to the plane of the waveguide core of RxPIC 80 chip, such as, for example, within $\pm 0.2^\circ$ relative to 90° from the horizontal plane of the as-grown epitaxial layers; otherwise, the light will be reflected up or down out of free space region 82. Etching along an outside edge, rather than an inside edge, in forming Echelle grating 84 is preferable for this reason too. Photodetectors 87(1) . . . 87(10) may be formed in the InP-based chip 80 as PIN photodiodes or avalanche photodiodes as taught in the previously incorporated application, Ser. No. 10/256,304 and in U.S. application publication No. 2003/0165314, published on Sep. 4, 2003, which publication is owned by the assignee herein and is incorporated herein by its reference. RxPIC chip 80 includes input waveguide 81 along one edge of the array waveguide 86. An incoming multiplexed signal in waveguide 81 diverges as it enters into free space region 82 and is reflected as well as diffracted by the grating so that different wavelength components of the multiplexed signal are directed and focused to the inputs 86A of respective waveguides 86. Thus, the first

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of such waveguides 86(1) may receive a channel signal, λ_1 , which is directed through waveguide 86 to photodetector 87(1). It should be noted that in order to make chip 80 smaller, waveguides 86 may be provided with 90 degree angular corners 89 rather than use a fan-out of waveguides as shown in the embodiment of FIG. 7. In this case, 45° mirrors may be etched at corners 89 for directing the light around these 90° waveguide corners and onto photodetectors 87. Each photodetector 87(N) may also have a corresponding output pad 88 for taking off-chip the photocurrents produced by photodetectors 87(N). The foregoing Echelle grating structure can also be employed in other embodiments of this invention, TxPIC and RxPIC alike.

Reference is now made to FIGS. 12 and 13 which show different versions of Echelle gratings that may be deployed with this invention. A shown in FIG. 12, the Echelle grating may be comprised of a series of flat etched steps 83A or as shown in FIG. 13, may be a series of angular steps 83B where, in each case, the diverging multiplexed beam is diffracted and reflected back as individual focused beams having different peak wavelengths.

While the invention has been described in conjunction with several specific embodiments, it is evident to those skilled in the art that many further alternatives, modifications and variations will be apparent in light of the foregoing description. Thus, the invention described herein is intended to embrace all such alternatives, modifications, applications and variations as may fall within the spirit and scope of the appended claims.

What is claimed is:

1. A monolithic transmitter photonic integrated circuit (TxPIC) chip comprising:

- a plurality of N signal generator channels integrated on the chip and formed in a spatial parallel array with each signal generator channel comprising at least one active element for generating a modulated signal;
- a wavelength selective combiner integrated on the chip that receives the modulated signals from each of said signal generator channels and combines them into a single multiplexed multi-wavelength signal, said combiner comprising an elliptical supergrating having N groups of subgratings, with open space regions formed at intersections of said subgrating groups, one subgrating group for each N signal, each of said subgrating groups comprising elliptically shaped arcs that have a period, Λ_m , and are positioned transversely relative to other subgrating groups to each receive a respective modulated channel signal and reflect the same back to a single common output waveguide;
- said single common output waveguide integrated on the chip as part of the spatial parallel array, said single common output waveguide interleaved between the signal generator channels.

2. The monolithic transmitter photonic integrated circuit (TxPIC) chip of claim 1 wherein said common output waveguide is parallel with and between one or more of said N signal channels.

3. The monolithic transmitter photonic integrated circuit (TxPIC) chip of claim 2 wherein said common output waveguide is between two groups of integrated signal channels at a position of N/2 in the spatial parallel array.

4. The monolithic transmitter photonic integrated circuit (TxPIC) chip of claim 1 wherein said common output waveguide terminates at an output chip facet adjacent to said active elements.

5. The monolithic transmitter photonic integrated circuit (TxPIC) chip of claim 1 wherein said supergrating is formed

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concurrently with the formation of the operational wavelength gratings for said active elements.

6. The monolithic transmitter photonic integrated circuit (TxPIC) chip of claim 1 wherein said active elements include laser sources that comprise DFB lasers or DBR lasers and electro-optic modulators that comprise electro-absorption modulators or Mach-Zehnder modulators.

7. The monolithic transmitter photonic integrated circuit (TxPIC) chip of claim 1 wherein said supergrating comprises a plurality of intermittently formed troughs.

8. The monolithic transmitter photonic integrated circuit (TxPIC) chip of claim 7 wherein said elliptical supergrating comprises N groups of subgratings, one subgrating group for each N signal, said intermittently formed troughs that have open space regions at intersections with intermittently formed troughs of another group of subgratings.

9. A monolithic transmitter photonic integrated circuit (TxPIC) chip comprising:

a plurality of N signal generator channels integrated on the chip and formed in a spatial parallel array with each signal generator channel comprising at least one active element for generating a modulated signal;

a wavelength selective combiner integrated on the chip that receives the modulated signals from each of said signal generator channels and combines them into a single multiplexed multi-wavelength signal, said combiner comprising an elliptical supergrating, wherein said elliptical supergrating comprises N groups of subgratings, one subgrating group for each N signal, each of said subgrating groups are comprised of a plurality of troughs having a period, Λ_n , and formed in a grating layer in said chip, wherein said troughs of each of said N groups when intersecting with troughs of another N group have an open space regions at the points of their intersection; and

a single common output waveguide integrated on the chip as part of the spatial parallel array, said single common output waveguide interleaved between the signal generator channels.

10. A method of forming a transmitter photonic integrated circuit (TxPIC) having a plurality of semiconductor layers, comprising the steps of:

forming a grating layer as one of the semiconductor layers;

forming a plurality of integrated optical signal channels on a substrate as part of the circuit, each signal channel comprising a laser source with a respective feedback grating to set the operational wavelength for each laser source different from each other laser source and a corresponding electro-optic modulator for producing a modulated channel signal;

forming an integrated wavelength selected optical combiner in the circuit, the combiner comprising one or more gratings; and

forming both the gratings for each laser source and the optical combiner in the grating layer.

11. The method of claim 10 wherein the optical combiner grating is a supergrating or an Echelle grating.

12. The method of claim 10 wherein the laser sources are DFB lasers or DBR lasers.

13. The method of claim 10 wherein the grating layer is a separate layer from an active region for the signal channels.

14. The method of claim 10 wherein the grating or gratings for the optical combiner comprise sets of subgratings.

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15. A monolithic transmitter photonic integrated circuit (TxPIC) chip comprising:

a plurality of signal generator channels integrated on the chip and formed in a spatial parallel array with each signal generator channel including a modulated source that together generate a plurality of modulated channel signals with different emission wavelengths;

a wavelength selective combiner integrated on the chip that receives the modulated channel signals from each of the modulated sources and combines them into a wavelength division multiplexed signal, said combiner comprising an elliptical supergrating comprising N groups of subgratings having open space regions formed at intersections if said groups of subgratings; and

a single common output waveguide integrated on the chip to transport the wavelength division multiplexed signal from the wavelength selective combiner to an exit from the chip, said single common output waveguide interleaved between the signal generator channels.

16. The monolithic transmitter photonic integrated circuit (TxPIC) chip of claim 15 wherein the combiner output waveguide exit is on an edge of the chip opposite a direction of the modulated channel signals.

17. The monolithic transmitter photonic integrated circuit (TxPIC) chip of claim 15 wherein the combiner output waveguide exit is between spaced portions of the spatial parallel array.

18. The monolithic transmitter photonic integrated circuit (TxPIC) chip of claim 15 wherein each of the subgrating groups comprising elliptically shaped arcs that have a respective period, Λ_n , with each subgrating group angularly disposed relative to other subgrating groups to each receive a respective modulated channel signal and reflect the same back to the combiner output waveguide exit.

19. The monolithic transmitter photonic integrated circuit (TxPIC) chip of claim 15 wherein the modulated sources in each signal channel comprise either direct modulated lasers or lasers with accompanying electro-optic modulators.

20. A monolithic transmitter photonic integrated circuit (TxPIC) chip comprising:

a plurality of signal generator channels integrated on the chip and formed in a spatial parallel array adjacent to and substantially parallel with one edge of the chip with each signal generator channel including a modulated source that together provide a plurality of modulated channel signals with different emission wavelengths;

an elliptical supergrating integrated on the chip that receives the modulated channel signals from each of the modulated sources and combines them into a wavelength division multiplexed signal;

a single output waveguide integrated on the chip that transports the wavelength division multiplexed signal from the elliptical supergrating output to an exit from the chip, said single output waveguide interleaved between the signal generators;

the elliptical supergrating comprising a plurality of groups of subgratings having open space regions formed at intersections of the subgrating groups, one subgrating group for each signal channel, each of the subgrating groups comprising elliptically shaped arcs that have a respective period, Λ_n , with each subgrating group angularly disposed relative to other subgrating groups to each receive a respective modulated channel signal and reflect the same back to the output waveguide exit.

21. A monolithic transmitter photonic integrated circuit (TxPIC) chip comprising:

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at least a first laser source having a laser source grating formed in a grating layer; and
a combiner having a supergrating for receiving an output of the first laser, said supergrating formed in the same grating layer as the laser source grating.

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22. The monolithic transmitter photonic integrated circuit (TxPIC) chips of claim **21** wherein the grating layer is AlInGaAs or InGaAsP.

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